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LAND UTILIZATION ISSUES FOR DEVELOPMENT
OF PICEANCE BASIN OIL SHALE

David S. Rubenson, Richard Y. Pei

January 1983

N-1928-DOE

Prepared for

The U.S. Department of Energy

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Rand
SANTA MONICA, CA 90406

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U.S. DEPARTMENT OF JUSTICE
FEDERAL BUREAU OF INVESTIGATION
WASHINGTON, D. C. 20535
MAY 1964

PREFACE

This Note documents the results of a study performed for the U.S. Department of Energy under Contract number DE-AC01-80PE70271. Its purpose is to provide the Office of Policy, Planning, and Analysis with a framework for quantitatively exploring the effects of federal land utilization policies on the potential of Piceance Basin oil shale.

Rand has developed an analytical methodology for predicting the stripping ratios obtained from oil shale surface mines. Stripping ratios are an indicator of mining costs, and use of this methodology will help explain the relationship between federal land utilization policies and the costs of resource extraction. In this study the authors also explore the effects of federal land utilization policies on the requirements for rapidly expanding an oil shale industry. A companion Note, The Effects of Lease Size on Yields from Oil Shale Surface Mines, N-1798-DOE, March 1982, addresses the effects of federal land policies on the amount of oil shale that can be extracted. The approach described here should be useful to researchers interested in federal land policies and the long-term use of Piceance Basin oil shale.

SUMMARY

This Note examines the effects of federal leasing policies on the costs and lead times required to extract Piceance Basin oil shale from surface mines. Application of current leasing policies would draw boundaries in the basin and assign developers to particular leases. This could result in limitations on the size of individual projects and present obstacles to mine expansion. Although understanding the impact of these constraints on mining costs requires a definitive cost analysis, this study shows that a first-order understanding can be obtained through the use of a parameter called the stripping ratio. The stripping ratio is shown to be related to mining costs and a method for calculating it is described. It should be emphasized that stripping ratios are only an indicator of mining costs; the results need to be confirmed by definitive cost analysis.

Our analysis shows that constraints on project size could increase the costs of extracting oil shale. Most shale is located in the center of the Piceance basin in very thick deposits that are covered by very thick overburden. This analysis shows that these deposits cannot be efficiently extracted at the 50,000 barrel per day (bpd) production levels typically contemplated by individual developers. Larger production levels (about 250,000 bpd) are needed to efficiently extract these deposits. The analysis also shows that constraints on mine expansion will increase the costs and lead times required to extract oil shale. Lead times are important because they represent the feasibility of rapidly expanding an oil shale industry in the event of a cut-off of

foreign oil supplies. A flexible leasing policy that allows exposed mine faces to be sold as a commodity is required to make full use of mine expansion and lower costs and lead times.

The nature of these constraints suggests that present leasing arrangements may not be suited to the unique character of the Piceance Basin shale resource. This analysis suggests that any policy that produces man-made boundaries and fragments the industry will adversely affect the development of oil shale. One alternative is to organize industry capability in the western edge of the basin, where shale can be efficiently developed at moderate production rates. Development could proceed unconstrained by boundaries. The center of the basin could be reserved until there is sufficient industry experience to undertake the large projects that are required.

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I. INTRODUCTION

Green River Formation oil shale represents an immense potential source of liquid hydrocarbons. This resource is confined to a small area in northwestern Colorado, northeastern Utah, and southwestern Wyoming. The thickest and richest oil shale deposits are located in a small region of northwestern Colorado known as the Piceance Basin. This basin, which occupies an area of only 1200 square miles, is estimated to contain more than 1200 billion barrels of equivalent oil in place.[1]

Most Piceance Basin oil shale is located on federal lands. The use of federal lands is governed by the Mineral Leasing Act of 1920. This act limits the size of federal leases to 5120 acres, prohibits off-site disposal of wastes, and prevents any single developer from obtaining more than one lease. A previous Rand analysis[2] showed that the 5120-acre limitation severely limits the amount of oil shale that can be extracted. In addition to limiting resource recovery, present leasing arrangements would produce a series of man-made boundaries which separate individual oil shale developments. The purpose of this Note is to show that man-made boundaries, and the associated industry fragmentation, will increase the cost and lead times required to extract oil shale with surface mining. Since ore extraction costs represent a major component of the selling price of shale oil,[3] this could be a

[1] U.S. Congress, Office of Technology Assessment, An Assessment of Oil Shale Technologies, Government Printing Office, Washington D.C., June 1980, p. 91.

[2] R. Y. Pei and D. S. Rubenson, The Effects of Lease Size on Yields From Oil Shale Surface Mines, N-1798-DOE, March 1982.

[3] Mining and crushing costs may represent more than 30 percent of the cost of an oil shale venture; see G. B. French, "Oil Shale Mining Update: Surface and Room and Pillar Systems," Fifteenth Oil Shale Symposium Proceedings, Colorado School of Mines Press, August 1982.

significant factor in the development of this resource. Lead times are important since it may be desirable to rapidly expand industry capacity in the event of a sudden reduction in foreign oil supplies. To examine these effects, we introduce a parameter called the stripping ratio. This parameter serves as a useful indicator of extraction costs and can be calculated without requiring a definitive cost analysis. Such a cost analysis would be beyond the scope of this study.

THE CHECKERBOARD SYNDROME

Despite the enormous potential of Piceance basin oil shale, the resource remains undeveloped. Over the last 50 years it has often appeared that development would occur. This has not happened because of changes in overall energy outlook and over optimistic initial cost estimates. As a result many proposed and partially designed shale projects have been canceled. These have included several projects that would have produced 50,000 bpd each. At the time of this writing, only one project of less than 10,000 bpd is being developed.[4]

Although there has been no production, there have been developments that could affect the future development of Piceance basin oil shale. Since most of the basin is owned by the federal government, the Mineral Leasing Act of 1920 is particularly important. At the present time two leases, Tracts C-a and C-b, have been granted under this law. The location of these leases is shown on the map of the Piceance basin displayed in Figure 1. This figure also shows that private lands have

[4] For a list of proposed projects see Colorado Energy Research Institute and Colorado School of Mines, Oil Shale 1982: A Technology and Policy Primer, November 1981, pp. 42-43. Among this list of projects only the 9,000 bpd Union Oil Project is being actively developed.

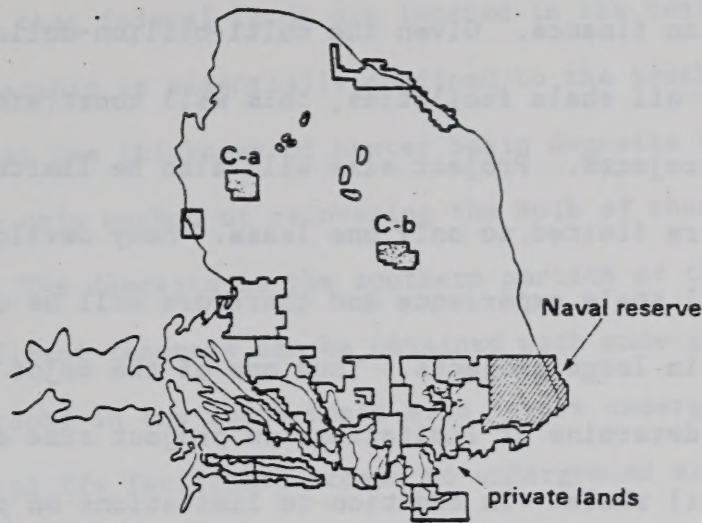


Fig. 1 -- Emergence of the checkerboard syndrome

been partitioned into individual tracts and that a trend toward dividing the basin into a "checkerboard" pattern has been initiated. Although there is still a large block of unpartitioned federal land, large parts of the basin have already been partitioned. The Mineral Leasing Act of 1920, and several proposed changes in this law, reinforce this pattern. Thus the basin may ultimately be divided by a set of man-made boundaries.

Man-made boundaries, coupled with other existing institutional arrangements, could limit the flexibility of an oil shale industry. In particular the limitation of one lease per developer, the requirement that lessees actively develop their own leases, and antitrust concerns could discourage a developer from participating in projects beyond his own lease boundaries. These factors will discourage large joint

ventures and limit the level of development to that which individual developers can finance. Given the multi-billion-dollar investments required for oil shale facilities, this will constrain the size of individual projects. Project size will also be limited by the fact that developers are limited to only one lease. Many developers will not have had prior oil shale experience and therefore will be unwilling to risk investments in large projects. Thus one of the major subjects of this study is to determine if limitations on project size affect the cost of extracting oil shale. In addition to limitations on project size, present leasing arrangements will encourage developers to sink new mines rather than expand mines that are already operating on other leases. This Note also examines the effects of this factor on the costs and lead times required to extract oil shale. It should be noted that the effects being studied are not a direct result of the 5120-acre limitation. Instead, they are a result of man-made boundaries and the present arrangements associated with leasing federal lands.

SURFACE MINING

This analysis concentrates on the effects of boundaries (and the associated limitations on flexibility) on the costs (as measured by the stripping ratio) of surface mining oil shale deposits on federal lands. Surface mining is important because it is the only technique that can lead to recovery of a significant fraction of the thick Piceance Basin shale deposits. The thickness of these deposits ranges up to 2000 ft. In underground mining only a thin seam is extracted, while other techniques such as modified in situ are as yet unproven.

The cost of extracting oil shale with surface mining is particularly important for the oil shale on federal land. This is

illustrated in Fig. 2 which shows four maps of the Piceance Basin. The first map indicates that federal lands are located in the center of the basin. Private ownership is essentially confined to the south. The second map shows that the thickness of center basin deposits ranges up to 2000 ft. The only method of recovering the bulk of these deposits is surface mining. The deposits in the southern portion of the basin are thin and significant recovery can be obtained with underground mining. The topography in the south basin also favors underground mining. The steep cliffs facilitate access to underground mines but make surface mining more difficult. The center of the basin is a large plateau that should be conducive to surface mining. Finally, the ratio of overburden to ore is smallest in the center of the basin. This ratio

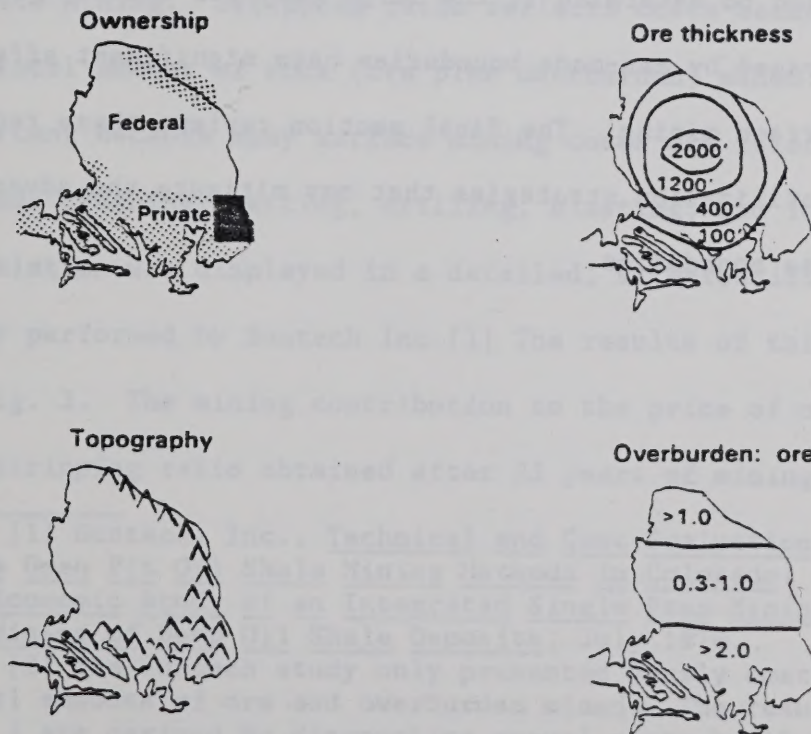


Fig. 2 -- Piceance Basin characteristics

gives some indication of the amount of overburden that must be removed to obtain a given quantity of ore. The larger values in the south basin indicate that surface mining may not be feasible. For this combination of reasons, extensive surface mining can only occur on federal lands in the central portion of the basin.

This Note explores the effects of present leasing arrangements on the costs of surface mining federal lands in the Piceance Basin. Due to the large level of effort required to perform a definitive cost analysis, we have chosen to utilize a parameter known as the stripping ratio to measure surface mining costs. This parameter is defined in the following section. The reasons making it a good indicator of mining costs are also discussed. This section also contains a description of a model for calculating this parameter. This model is exercised in the following section to determine if the large projects and mine-expansion options discouraged by man-made boundaries have significant effects on the cost of surface mining. The final section reviews these results and suggests land utilization strategies that may mitigate the adverse effects of lease boundaries.

II. THE STRIPPING RATIO MODEL

In this section we introduce a parameter known as the stripping ratio, which will serve as a useful tool for examining the effects of man-made boundaries on the cost of extracting oil shale. The stripping ratio is defined by the following formula:

$$\text{Stripping ratio} = (\text{overburden mined})/(\text{ore mined})$$

Stripping ratio is a useful parameter because it can be calculated analytically and it reflects the costs of surface mining. It is often used by industry as a quick method of determining the feasibility of surface mining. Stripping ratio reflects costs because it is related to the total amount of rock (ore plus overburden) mined. Total rock is important because many surface mining costs are related to it. These include crushing, wetting, drilling, blasting, and loading. This correlation was displayed in a detailed, site-specific, surface mining study performed by Suntech Inc. [1] The results of this study are shown in Fig. 3. The mining contribution to the price of oil correlated with the stripping ratio obtained after 25 years of mining. [2] These results

[1] Suntech, Inc., Technical and Cost Evaluation of Candidate Large Scale Open Pit Oil Shale Mining Methods in Colorado: Vol. I, Technical and Economic Study of an Integrated Single Pass Mining System for Open Pit Mining of Deep Oil Shale Deposits, July 1976.

[2] The Suntech study only presented yearly cost totals and the annual amounts of ore and overburden mined. The results presented in Fig. 3 are derived by discounting annual costs by 10 percent per year. Different values of the discount factor only slightly alter the relationship shown in Fig. 3 and do not alter the conclusion that stripping ratio is a reasonable indicator of mining costs.

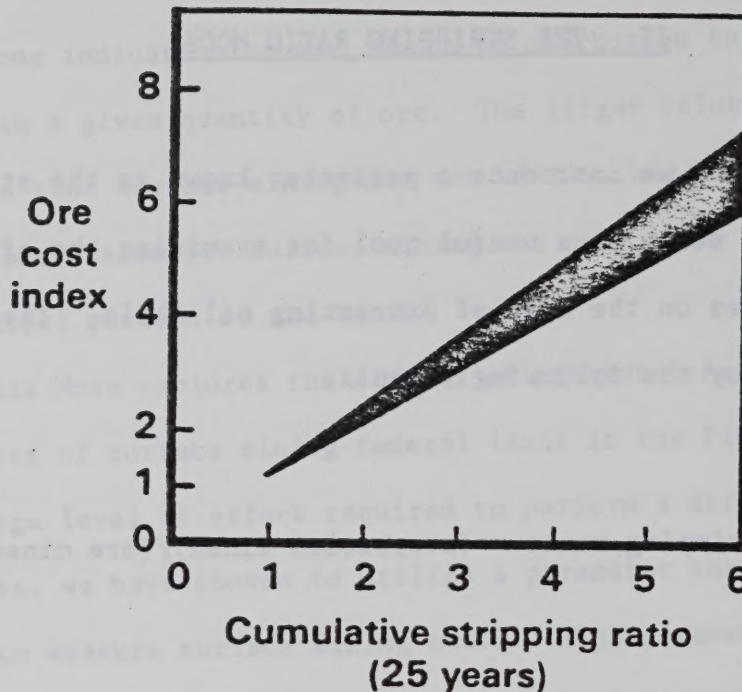


Fig. 3 -- Results of a site-specific study

are based on surface mines producing 500,000 and 1,250,000 tons of ore per day (equivalent to 250,000 and 625,000 bpd for 20 gallon/ton shale). The Suntech study indicated some breakdown in the correlation for stripping ratios above 3 or 4. This is a result of the increased haulage costs associated with extremely large mines. Stripping ratios do not reflect haulage distances. The correlation with costs breaks down when mines with significantly different haulage profiles are compared. Stripping ratios therefore should be used only as a rough and simple-to-use indicator of cost trends. It should not be viewed as a substitute for definitive cost analysis.

Since stripping ratio is defined as the amount of overburden mined per unit of ore, it may appear that the ratio of overburden thickness to ore thickness would produce the stripping ratio. However, for practical mining operations, several parameters affect the stripping ratio:

- Overburden thickness
- Ore thickness
- Mine wall slopes
- Mine width
- Production rate
- Mine lifetime

The stripping ratio cannot be lower than the ratio of overburden thickness to shale thickness. The other parameters increase the value of the stripping ratio. Since mine walls must be sloped to maintain stability, the upper portion of a mine (which contains overburden) will be wider than the deeper portion (which contains shale). Thus sloped mine walls increase the stripping ratio. The effects of these sloped walls can be minimized if the mine is extremely wide. In a realistic mining operation, however, an initial layer of overburden must be removed prior to extracting any oil shale. The quantity of initial overburden increases with mine width.[3] Wide mines may be acceptable if the production rate is sufficient to allow initial overburden removal in a time that is short compared with the lifetime of the mine.

The effects of these parameters can be better understood by considering the difference between the cumulative and annual stripping ratios. Figure 3 shows the relationship between costs and cumulative stripping ratio. Cumulative stripping ratio represents the total amounts of waste and ore mined. This differs from the stripping ratios obtained during individual years. Annual stripping ratios vary with time. The source of this time dependence is illustrated in Fig. 4,

[3] Mine width is in and out of the page in Fig. 4.

which shows an oil shale surface mine at different stages of development. The first frame shows the initial deposit. The second frame shows the initial mining period, during which only overburden is mined and the stripping ratio is infinite. The amount of overburden mined before shale is extracted is determined by the slopes of the mine walls and the mine width. Based on our previous analysis,[4] we have assumed the mine walls are sloped at 41 degrees. The working face is assumed to have a 19-degree slope. The mine width is a function of production rate. As mine depth increases, the stripping ratio decreases. At final depth (fourth frame), the stripping ratio reaches a

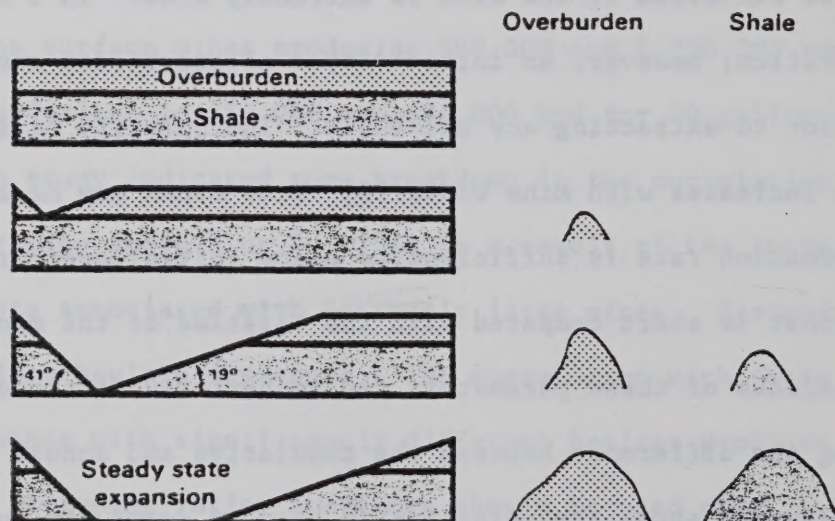


Fig. 4 -- Development of an oil shale surface mine

[4] Pei and Rubenson.

steady-state condition. After this point, the cumulative stripping ratio begins to approach the value of the steady-state stripping ratio.

Figure 5 illustrates the difference between yearly and cumulative stripping ratios with data from the definitive design plan of federal lease tract C-a (this design plan was never implemented). [5] The bars represent annual stripping ratios. The curve marked "cumulative" represents the stripping ratios for the entire process. For example, after eight years the cumulative stripping ratio is approximately 1.50. This value consists of the total waste and total ore mined up to and including the eighth mining year.

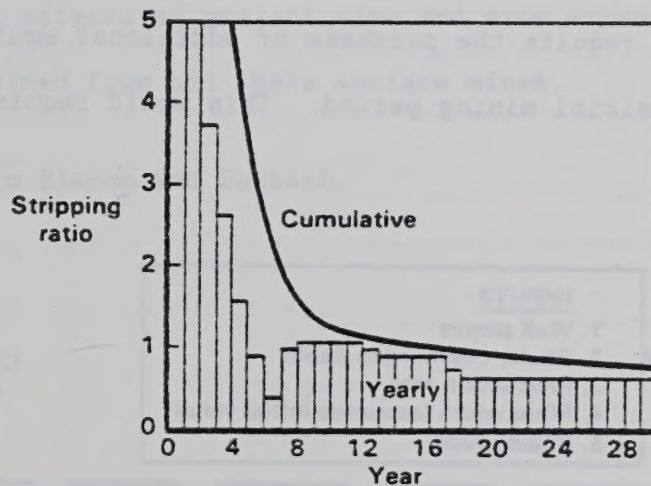


Fig. 5 -- Stripping ratios for Tract C-a

[5] Kio Blanco Oil Shale Project, Detailed Development Plan, Tract C-a, Volume 3, Gulf Oil Corporation and Standard Oil Company (Indiana), March 1976.

We have developed an analytical model that calculates stripping ratios for oil shale surface mines. Model assumptions and algorithms are described in App. A. Figure 6 displays an overview of this model. Mine wall slopes, thickness of overburden and shale, shale grade, the steady state production goal, and the mine width (the distance in and out of the page in Fig. 4) are inputs. Mine width is optimized in later steps. These input parameters determine the steady-state mine geometry. The steady-state geometry allows for prediction of the steady-state stripping ratio and amount of rock (ore plus overburden) extracted during a steady-state mining year. We assume this extraction rate is constant for the entire mining process. It is of course possible for a developer to remove the initial overburden at greater rates; however, such action would require the purchase of additional equipment for use only during the initial mining period. This would require a significant

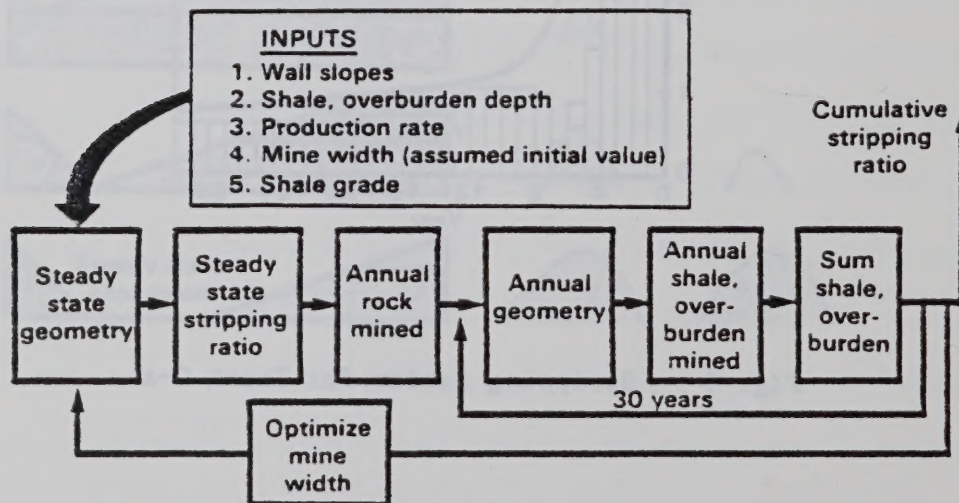


Fig. 6 -- The Rand Stripping Ratio Model

front-end investment, which would have an adverse effect on the selling price of shale oil. The difficulty in accelerating the initial mining phase is also indicated in two site-specific studies[6] which show the mining rate prior to steady state to be less than that at steady state.

Once the annual rock production is calculated, the geometry for each mining year can be predicted. The amount of shale and overburden extracted during each year is calculated and summed with previous years. This procedure is repeated for all mining years. We assume that 30 years represents the time used to evaluate the profitability of a particular development. The procedure is repeated until an optimal value of mine width (determined by minimizing the cumulative stripping ratio) is found. In the next section we utilize this procedure to examine the effects of project size and mine expansion on the stripping ratios obtained from oil shale surface mines.

[6] Rio Blanco and Suntech.

III. APPLICATION TO THE PICEANCE BASIN

As stated in the introduction, present leasing arrangements may constrain the size of individual projects and limit the use of mine expansion. In this section we use the stripping ratio model to determine the significance of these two factors. Before applying the model, it should be pointed out that the importance of these two effects may vary with different deposits. Figure 7 shows an east-west cross-section of the central basin. The left edge of this cross-section begins at the western edge and extends eastward, about two-thirds of the way across the basin.[1] The deposits fall into two broad categories: center basin and western edge. Center basin deposits are more than

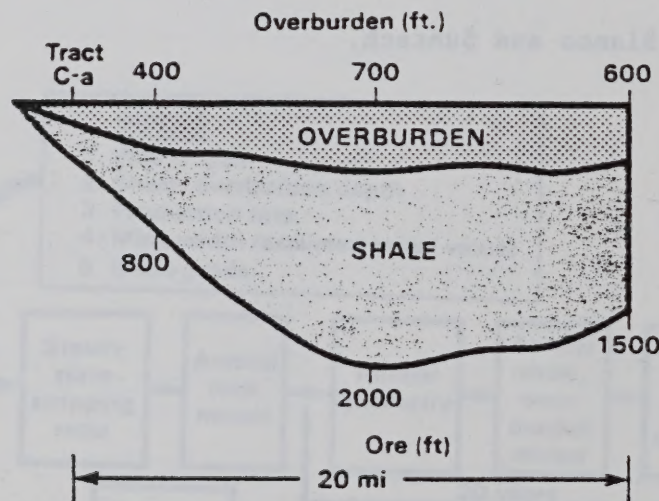


Fig. 7 -- Central basin cross-section

[1] For clarity, the depth scale in Fig. 7 differs from the horizontal scale.

1500 ft thick and are covered by more than 600 ft of overburden. Deposits on the western edge of the basin are thinner and are covered by less overburden. Figure 7 also shows that lease Tract C-a is located on the western edge of the basin.[2] In this analysis we examine the effects of project size and mine expansion for both center basin and western edge deposits.

CONSTRAINTS ON PROJECT SIZE

If an active leasing program fragments industry capability, then the size of individual projects will be constrained by the financial resources of individual developers. Typically, 50,000 bpd have been the largest plant contemplated by individual developers and even these have been estimated to cost several billion dollars.[3] Figure 8 shows the results obtained from the stripping ratio model for two 50,000 bpd plants: one with an 800-ft deposit and 400 ft of overburden, and the other a 2000-ft deposit with 700 ft of overburden. The former represents a lease on the western edge while the latter represents a lease in the center of the basin. Figure 8 also shows stripping ratios obtained from the definitive plan for Tract C-a.[4] The close agreement of the Tract C-a data with those of the 800-ft shale deposit provides a confirmation of the model. The Tract C-a data also provide an

[2] Tract C-a is actually located to the north (into the page) of the cross-section illustrated in Fig. 7. It is shown here to indicate the relative thickness of the deposits on this tract.

[3] Some developers have contemplated eventual expansion to 100,000 bpd after successful completion of a 50,000 bpd plant.

[4] Rio Blanco Oil Shale Project.

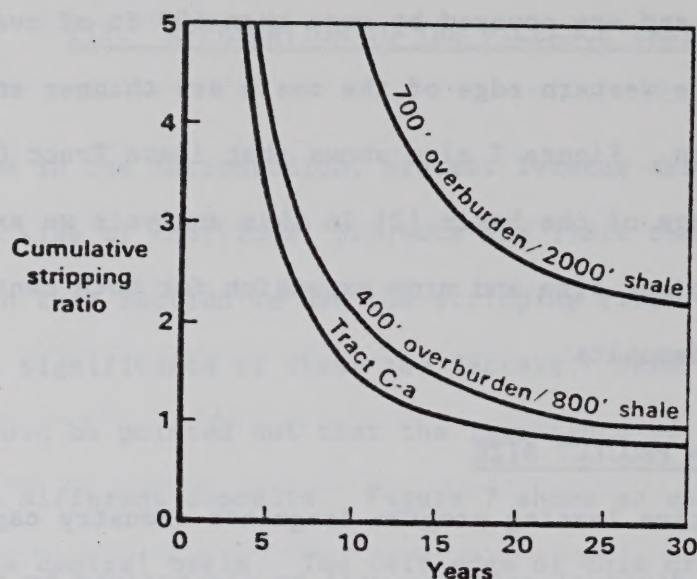


Fig. 8 -- Cumulative stripping ratios for 50,000 bpd

indication of the stripping ratios required for development to be seriously considered.

Figure 8 shows that stripping ratios for center basin deposits are higher than those on the western edge. It may therefore be more costly to extract center basin deposits. This is a result of the 50,000 bpd production rate. At 50,000 bpd an individual developer would not open a mine wide enough to reduce the adverse effects of removing 700 ft of overburden. Our model predicts that for a 50,000 bpd mine in the center of the basin, a minimum stripping ratio is obtained with a mine width of 5000 ft.[5] This width is insufficient to support the full resource depth and minimize the adverse effects of the sloped mine walls. At 50,000 bpd, larger widths are not desirable because more initial overburden removal is required. With larger production rates there is

[5] For the western edge deposit the optimum width is 4000 ft.

more equipment available for overburden removal and larger widths become practical. Figure 9 shows the effects of production rate on the cumulative stripping ratio obtained after 30 years of mining. The stripping ratio decreases with increased production. At rates of 250,000 bpd, the stripping ratios begin to approach the values that can be obtained on the western edge of the basin. Western-edge stripping ratios also improve with production rate but they are less sensitive to mine size. It should be reemphasized that these economies of scale should be confirmed by a cost analysis that incorporates haulage profiles and discount factors. Nonetheless, the dramatic improvement in stripping ratios for center basin deposits appears to indicate economies of scale. Further discussion is provided in App. B.

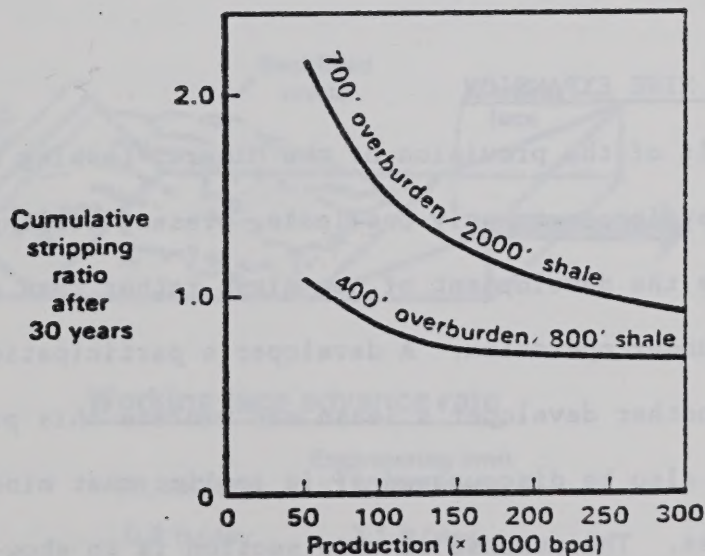


Fig. 9 -- Thick deposits require large production

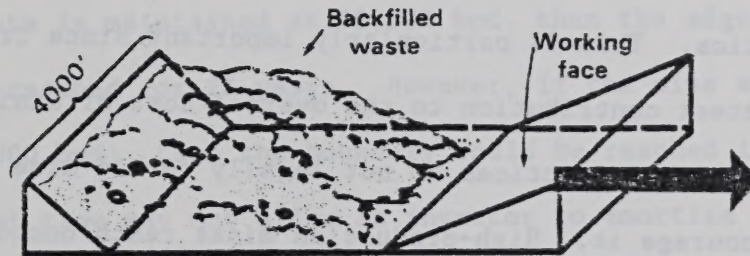
Figures 8 and 9 imply that present and proposed leasing practices could increase the cost of extracting center basin shale. If the basin is divided into several tracts, it is unlikely that individual developers will be able to marshal the financial resources needed for the super-sized projects indicated in Fig. 9. Previous studies by individual developers have concentrated on 50,000 bpd plants at costs of several billion dollars. At the time of this writing, the only active shale project has a production goal of less than 10,000 bpd. It should also be remembered that a 50,000 bpd mine would require approximately 100,000 tons per day of 20-gallon-per-ton shale. This is comparable to the largest surface mine in the United States. It is clear that special arrangements to concentrate industry capability will be required to extract center basin shale at favorable stripping ratios. Failure to do this could result in increased costs for extracting the bulk of the shale resource.

CONSTRAINTS ON MINE EXPANSION

As a result of the provision of the Mineral Leasing Act of 1920 which limits developers to only one lease, present leasing practices could encourage the development of new mines rather than expansion of mines already under operation. A developer's participation in a mining operation on another developer's lease may violate this provision. Mine expansion will also be discouraged if it implies that mines will cross lease boundaries. The purpose of this section is to show that if mine expansion is discouraged, then the cost of extracting shale, as well as the amount of time required to expand a shale industry, will be adversely affected.

Extraction Costs

Mine expansion represents an opportunity to reduce the costs of extracting oil shale. Figure 8 shows that a significant portion of surface mining costs can be attributed to initial overburden removal. This initial period is extremely important in financial analyses where downstream costs are heavily discounted. Expansion of existing mines may represent one method of increasing production without high stripping ratios during the initial years. One mine expansion method is illustrated in Figure 10, which shows a 50,000 bpd mine located on the western edge of the basin. The stripping ratio model predicts that the optimal width is about 4000 ft. Narrower mines produce higher stripping ratios because of the sloped mine walls, while wider mines are less



Working face advance rate

	Engineering limit (130,000 bpd)
50,000 bpd	
0.8 ft/day	2.1 ft/day

Fig. 10 -- Mine expansion capability
(400 ft. overburden, 800 ft. shale)

favorable due to initial overburden removal. Although this mine was optimized for 50,000 bpd, it could be expanded when steady state conditions are achieved. Ultimate capacity is limited by the area (projection of the area in the mining direction) of the working face and the rate at which a given area can be mined. A study by the Sun Oil Company[6] identified an engineering limit of about 0.15 tons per square foot. This is equivalent to a working face advance of about 2.1 ft/day. At 50,000 bpd the mine face advances at 0.80 ft/day. Thus, a mine initiated for 50,000 bpd can be expanded to a total capacity of 130,000 bpd.

Limitations on mine expansion could increase the cost of extracting shale. Figure 11 compares the cumulative stripping ratio for an expanded mine[7] and a new mine. This figure shows that an expanded mine achieves steady-state stripping ratio immediately, while a new mine must go through the development phases, which produce very high stripping ratios. This is particularly important since front-end costs make the greatest contribution to the overall cost of mining.

Present leasing practices do not legally forbid mine expansion, but they may discourage it. High-production mines reach boundaries faster than low-production mines. If, for example, lease size is maintained at 5120 acres (with off-site disposal), a square mine on such a lease might be 13,000 feet on a side.[8] The length of the mine shown in Fig. 10

[6] C. E. Banks et al., Technical and Economic Study of an Integrated Single Pass Mining System for Open Pit Mining of Deposits, Phase I, Sun Oil Company, Richardson, Texas, April 1975, p. 5-129.

[7] The expanded mine represents a production increase from 50,000 bpd to 100,000 bpd.

[8] This area is less than 5120 acres due to requirements that the process facilities be located on site. See Pei and Rubenson.

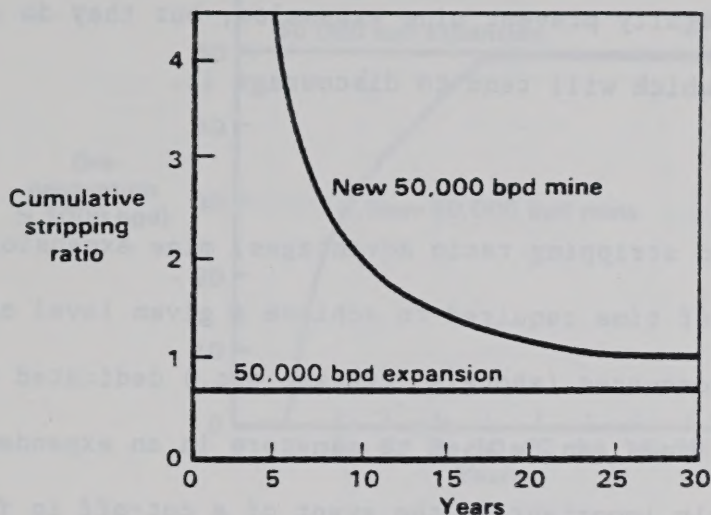


Fig. 11 -- Mine expansion results in favorable stripping ratios

would be about 5,000 feet when it first reached steady state. If the mining rate is maintained at 50,000 bpd, then the edge of the lease would not be reached for 27 years. However, if the mine advanced at 2.1 ft/day (130,000 bpd), then the boundary would be reached in 10 years. This period of time may not allow an investor to amortize his investment in the required process facilities. Another factor inhibiting mine expansion is the capital required for increased production. As with center basin deposits, it may be difficult for a single developer to marshal the financial resources required to fully exploit an existing mine. Bringing in partners may also be problematic. Unless a partner's process facilities can be sited nearby, there may be very large haulage costs. Partners may also be under a legal obligation to develop their

own leases rather than use ore from another. Large partnerships could also raise antitrust concerns. Thus present and proposed leasing practices do not legally prevent mine expansion, but they do contain a number of factors which will tend to discourage it.

Lead Times

In addition to stripping ratio advantages, mine expansion can reduce the amount of time required to achieve a given level of production. The resources (shovels, trucks, etc.) dedicated to removing overburden in new mines can be used to mine ore in an expanded mine. This is particularly important in the event of a cut-off in foreign oil supplies. Mines represent the longest lead-time items in an oil shale facility. Present leasing policies, which may discourage mine expansion, may increase the time required for mine development. This may also result in decreasing the nation's ability to respond to a sudden reduction in oil supplies.

Figure 12 compares the ore production of a new 50,000 bpd mine on the western edge of the basin (pictured in Fig. 10) with that of an expanded mine. A new mine does not reach steady-state production until year 10. The expanded mine achieves full production immediately. Since mines represent one of the longest lead-time items in a shale project, the ability to expand mines could represent a significant benefit in attempting to achieve rapid industry expansion.

If rapid expansion is needed during the early stages of an oil shale industry, then there may only be one or two operating surface mines. Expanding these mines to 130,000 bpd would not make a significant impact on national energy supplies. If, however, there is advanced planning, or a different set of incentives from those now in

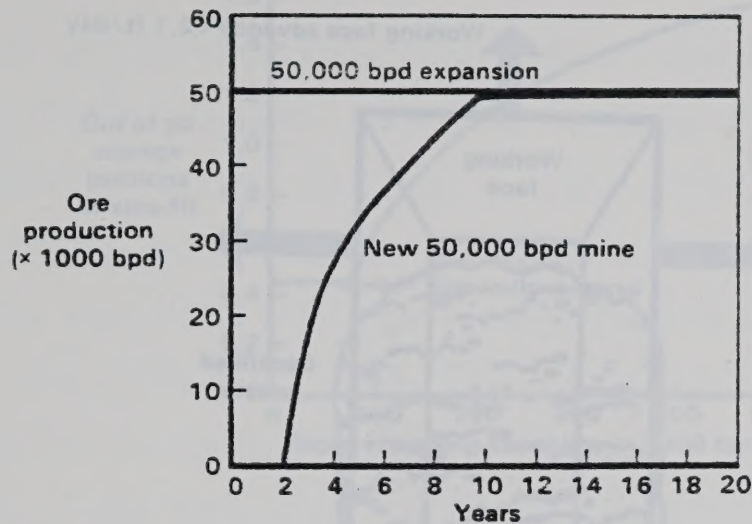


Fig. 12 -- Yearly production for a 50,000 bpd steady state mine

place, additional rapid expansion capability may be possible. Added capability could be achieved by expanding the sidewalls, as shown in the plan view of a mine pictured in Fig. 13. However, sidewalls represent rapid expansion capability only if backfilled waste does not block access to these walls. Backfilled waste would have to be removed prior to mining. Although blasting and drilling costs may not be incurred, the costs of removal would be significant and the process could require several years. If sidewalls are to provide rapid expansion capability, additional waste must be stored out of the pit and away from the mine.

Sidewall expansion is important because it can dramatically increase the extent to which an already operating mine can be expanded. Figure 14 shows the out-of-pit volume as a function of the rapid expansion capability of a 50,000 bpd steady-state mine located on the

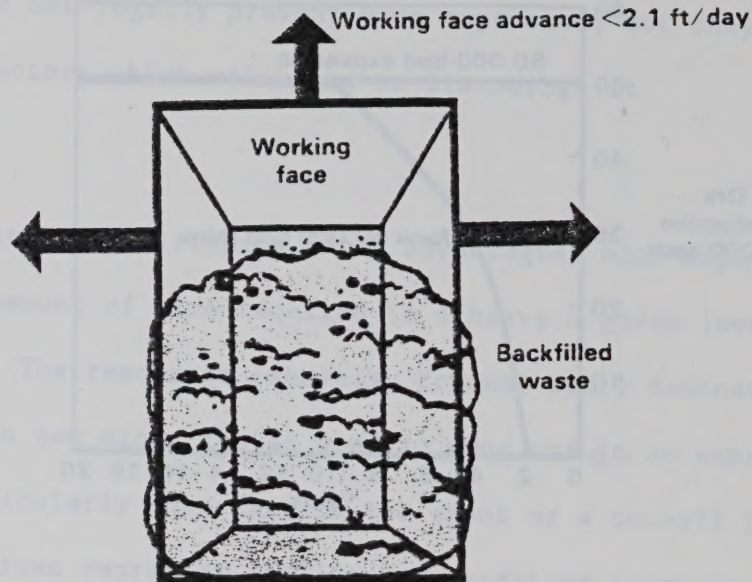


Fig. 13 -- Sidewall expansion

western edge of the basin. The figure shows that 4.5×10^5 acre-ft must be stored out of the pit for initial development. The first 80,000-bpd expansion occurs along the original mine working face and no additional out-of-pit storage is required. Additional rapid expansion capability requires additional out-of-pit storage. If the proper incentives are in place, such out-of-pit storage could dramatically increase the speed at which a small oil shale industry can be expanded.

Under the present leasing arrangements there is no incentive to store additional quantities of waste out of the pit. Out-of-pit storage requires larger haulage profiles and is more expensive than storing in the pit. Without off-tract lands, out-of-pit storage would not produce the desired effect, because waste would have to be stored next to the

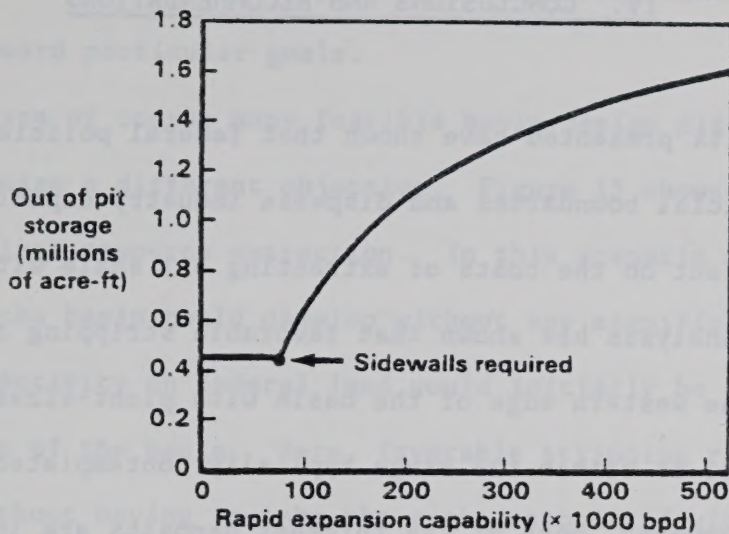


Fig. 14 -- Rapid expansion capability

mine and would continue to block sidewall expansion. Off-tract lands, and incentives to place additional waste on these lands, are required to make the sidewalls represent rapid expansion capability. One method of motivating additional out-of-pit storage is through federal financial incentives. Another is to allow developers to sell exposed mine faces as a commodity. In this latter method, sidewalls could be purchased by other companies that wish to expand an already existing mine. However, it would be necessary that these companies be able to site process plants on federal land near the expanded mine. In any case, advanced planning and a flexible leasing policy will be required.

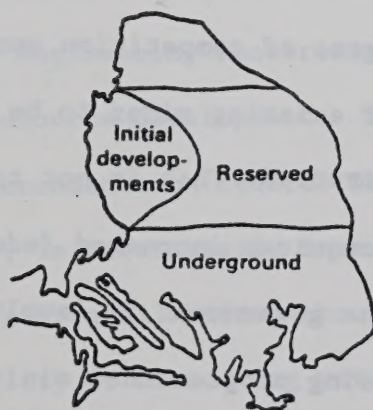
IV. CONCLUSIONS AND RECOMMENDATIONS

The results presented have shown that federal policies which produce artificial boundaries and disperse industry capability may have an adverse effect on the costs of extracting oil shale with surface mining. The analysis has shown that favorable stripping ratios can be obtained on the western edge of the basin with plant-sizes of 50,000 bpd. This size is within the range typically contemplated by developers. However, most of the thickest deposits are located in the center of the basin. Here, production levels of at least 250,000 bpd are required to obtain favorable stripping ratios. A private developer is unlikely to undertake a venture of this size. Thus dispersion of industry capability could increase the costs of extracting center basin deposits. The results also indicate that policies which restrict mine expansion could increase the cost of mining and the amount of time required to expand the industry.

Innovative approaches to land utilization policies are required to allow for efficient use of the oil shale resource. Federal lands have traditionally been released through the leasing process. However, Piceance Basin oil shale is a unique resource. Its limited geographic distribution implies that individual developments will be interactive. As an example, the process facilities and waste disposal sites from one development could interfere with other developments. Optimal utilization of Piceance Basin oil shale can only be achieved if these interactive effects are accounted for. It may therefore be useful to organize land utilization policy around an overall engineering design of

the Piceance Basin. Such an approach would ensure that policies are directed toward particular goals.

There are of course many feasible basin design plans, each of which could emphasize a different objective. Figure 15 shows one scenario that emphasizes resource extraction. In this scenario the southern portion of the basin could develop without any significant degree of planning. Activity on federal land would initially be confined to the western edge of the basin. Here, favorable stripping ratios can be obtained without having to take the risks associated with super-sized projects. These mines would initially be developed for individual plants but could be expanded later. There would be no lease boundaries and mine expansion could be dictated by economic incentives. In this scenario the central basin would be reserved. It could be developed



- Private sector and government agree on initial sites
- No lease boundaries
- Maximum flexibility
 - Consortia
 - Mine expansion capability
- Carefully sited disposal sites
 - Canyons
 - Low grade deposits
 - Basin edges

Fig. 15 -- A basin-wide development scenario

when there is sufficient industry experience to undertake the risks associated with super-large projects or when innovative techniques allow for efficient extraction of these deposits. Leaving this area untouched would also allow industry to concentrate its capability in the western edge of the basin.

The obvious difficulty with this scenario is developing and implementing policies that stimulate this pattern. To some extent maximum private sector flexibility is required. Large consortiums and the ability to use mine expansion as a commodity are required. Market forces, unconstrained by artificial boundaries and limitations on scale, may allow for the benefits associated with mine expansion and increased out-of-pit disposal. Another approach may be to decouple the mining and processing operations. Mines could be owned by the government, with process facilities owned by individual developers. Such an approach would allow for the large-scale operations needed for efficient mining while still allowing a significant degree of competition among shale oil processors. This would also allow for existing mines to be expanded when new process facilities were constructed. This is not to say that an organized basin development strategy requires increased federal involvement. By fact of ownership, the government is involved in the development of oil shale. Even a leasing program that minimizes federal involvement will result in a development pattern dictated by the way in which the leasing program was implemented. It would therefore be prudent for the government to develop objectives for the resource and implement policies aimed at accomplishing those objectives.

The analysis presented in this Note suggests a broad range of additional research that is needed to arrive at a comprehensive oil shale land utilization strategy. Most apparent is the need to expand the stripping ratio model. Piceance Basin geology, topography, and hydrology could have important effects on overall development. These factors should be incorporated in an expanded model. It would also be desirable to analyze mining costs in addition to stripping ratios. A cost analysis would provide greater insight into the importance of haulage profiles. This information could be used to develop a logical approach for siting waste disposal areas and process plants. Finally, it will be important to consider the effect of advanced technologies on land utilization requirements. Advances in mining or shale processing may give rise to new land utilization requirements. The potential for such advances should be considered, and the implications incorporated in a comprehensive land utilization strategy.

In a broader sense, this Note illustrates the importance of considering engineering requirements in the analysis of policies affecting resource development. This pertains to most resources, but given the dependence on federal water policies and environmental regulations, is particularly important for shale development. Policies affecting water availability should be formulated with consideration for the possibility of conserving water in the shale conversion process, and the costs of that conservation. Air pollution regulations provide another example. Existing policies may prevent large centralized projects and give rise to the "checkerboard syndrome" described in this text. Thus there is an interaction between air pollution regulations

and land utilization policies. An analysis of this relationship should also consider the costs and technical feasibility of minimizing emissions. This would result in a better understanding of the relationship among allowable land utilization policies, emission control costs, and protection of the environment.

Appendix A

STRIPPING RATIO MODEL

This appendix reviews the assumptions and algorithms used to derive the stripping ratios presented in the text. The appendix is organized in a manner that follows the logic-flow diagram in Fig. 6. This figure shows that the input parameters (wall slopes, shale depth, overburden depth, and production rate) allow prediction of mine geometry under steady-state conditions. This determines the rate at which total rock (ore plus overburden) is mined. With this value, mine geometry can be predicted for each of the 30 years of mining. The procedure is repeated until an optimal mine width, determined by the minimum in the cumulative stripping ratio, is found.

INPUTS

The inputs to the stripping ratio model are the slopes of the mine walls and the working face, the shale and overburden depth, the steady-state production rate, the average shale grade, and the mine width. Mine width is later optimized. As stated in the text, we have assumed that the mine walls are sloped at 41 degrees and the working face is sloped at 19 degrees. These values were taken from the two site-specific studies referenced in the text. Shale depth, overburden depth, and steady-state production rate are determined by the particular mine being studied. The thicknesses shown on the cross-section in Fig. 7 are based on deposits averaging 20 gallons per ton, and this value is used in the analysis.

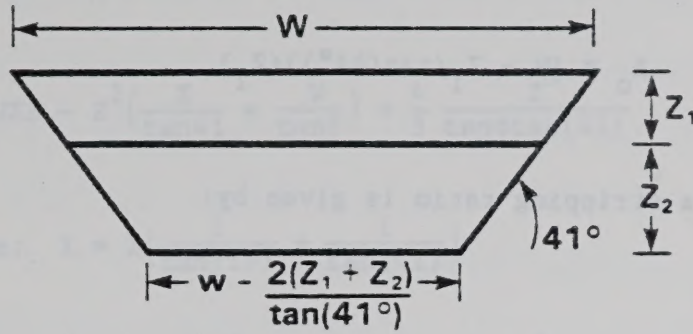
STEADY-STATE CONDITIONS

The input parameters can be used to construct the dimensions of the steady state mine working face. The vertical projection of the working face area is illustrated in Fig. A.1. The vertical projection of the area is important because the mine is expanded along the horizontal direction. The sum, $(Z_1 + Z_2)$, represents the mine depth. This depth is not necessarily equal to the depth of the overburden and shale. The inequality arises if the mine width is insufficient to support the full depth. This latter constraint is given by the following expression:

$$500 + \frac{2(Z_1 + Z_2)}{\tan(41^\circ)} \leq W \quad (1)$$

all dimensions in feet

Equation (1) gives a constraint on mine depth assuming the requirement of a 500-ft mine floor. For the two cases analyzed in the text, total depths of 1200 ft and 2700 ft were required to fully exploit the resource. These depths require minimum mine widths of 3260 and 6711 ft respectively. Figure A.1 also illustrates why stripping ratios improve with higher production. As the mine width increases, the effects of the sloped mine walls decreases and the steady-state stripping ratio approaches the overburden-to-shale ratio. However, large widths increase the amount of overburden that must initially be removed. Thus a large rock-mining rate is required. As discussed later, this corresponds closely with the production rate.



Z_1 = Overburden thickness

Z_2 = Shale thickness

Fig. A.1 -- Vertical projection of the steady-state working face

Using Eq. (1) to determine allowed mine depth (given mine width), the dimensions of the steady-state working face can be calculated. The area on the working face that is covered by shale is given by:

$$A_s = \left(W - \frac{2Z_1}{\tan(41^\circ)} - \frac{Z_2}{\tan(41^\circ)} \right) Z_2 \quad (2)$$

where Z_2 is determined in Eq. (1).

The area of the overburden on the working face is given by:

$$A_o = (W - Z_1/\tan(41^\circ))(Z_1) \quad (3)$$

The steady-state stripping ratio is given by:

$$\text{Steady state stripping ratio} = A_o/A_s \quad (4)$$

Using these formulas and the steady-state production goal, the annual amount of rock (overburden plus shale) mined is calculated. This value is given by the following expression:

$$\text{Annual rock mined} = (2)(14 \text{ ft/ton})365(P)(A_o + A_s)/A_s \quad (5)$$

where (P) is the production rate in barrels per day.

The factor of 2 converts barrels per day into tons of 20-gallon/ton shale.

MINING PRIOR TO STEADY STATE

As stated in the text, we have assumed that the total quantity of rock mined is constant throughout the mining period. The quantity of rock given by Eq. (5) can be used to predict the mine geometry at various points in the process. We have assumed that the mine develops with a wedge-shaped opening, as shown in Fig. 4. The volume removed

from the deposit is illustrated in Fig. A.2. The volume of this wedge is given by the following formula:

$$V = WXZ - Z^2 \left(\frac{X}{\tan 41} + \frac{W}{\tan \theta} \right) + \frac{4}{3} \frac{Z^3}{\tan \theta \tan(41)} \quad (6)$$

$$\text{where: } X = Z \left(\frac{1}{\tan(19)} + \frac{1}{\tan(41)} \right)$$

$$\theta = \arctan \left[\frac{2 \tan(41) \tan(19)}{\tan(19) + \tan(41)} \right]$$

The symbol θ is used only for notational convenience.

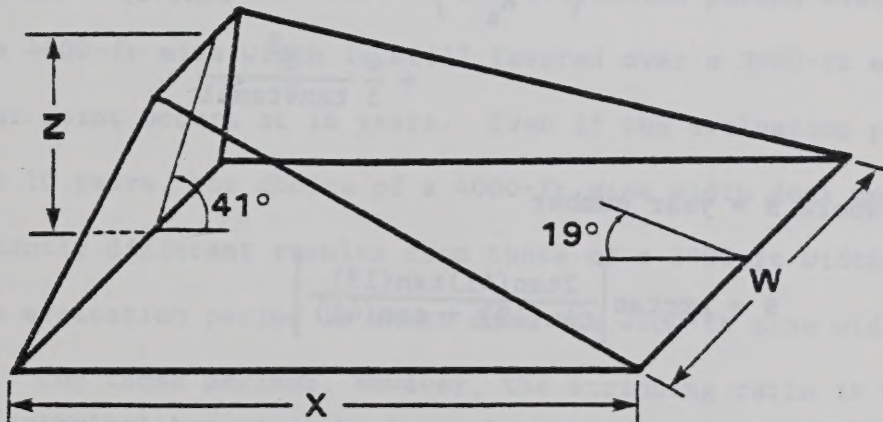


Fig. A.2 -- Volume of rock removed prior to steady state

This volume may consist only of overburden or may contain both overburden and shale. If $Z < Z_1$ then the volume contains only overburden and the stripping ratio is infinite. If $Z > Z_1$ then the overburden volume can be calculated using Eq. (6) with $Z = Z_1$. Subtracting the overburden volume from the the total rock gives the amount of shale contained in the wedge.

Equations (5) and (6) can be used to calculate the cumulative stripping ratios obtained at each year in the process. This is done by solving the following equality for the depth of the wedge (Z):

$$(N) \left(\begin{array}{l} \text{Annual rock} \\ \text{mined in ft}^3 \end{array} \right) = \text{Volume of the mined wedge}$$

$$(2)(N)(14)(365)(P) \left(\frac{A_o + A_s}{A_s} \right) = WXZ - Z^2 \left(\frac{X}{\tan(41)} + \frac{W}{\tan\theta} \right) + \frac{4}{3} \frac{Z^3}{\tan\theta \tan 41} \quad (7)$$

where N = year number

$$\theta = \arctan \left[\frac{2 \tan(41) \tan(19)}{\tan(19) + \tan(41)} \right]$$

Equation (7) defines the total volume mined up to and including the Nth mining year. The amount of overburden and shale can also be calculated using the method discussed above. Thus the cumulative stripping ratio can be obtained for any year prior to steady state. The annual stripping ratios can be calculated by comparing cumulative stripping ratios from consecutive years.

MINE-WIDTH OPTIMIZATION

The above procedure uses mine width (W) as an input parameter. This parameter is optimized by repeating the above procedure with different values of the mine width. The optimal value is the one which minimizes the cumulative stripping ratio after a given evaluation period. Smaller widths require less overburden removal but have less favorable steady-state stripping ratios. Thus the optimal width will depend on the evaluation period used, the large widths being optimal for longer evaluation periods. The results presented in the text are based on an evaluation period of 30 years. This time period was based on the definitive design plan for Tract C-a, which considered an equivalent period. Choosing this time period resulted in a mine width of 4000 ft for the 800-ft deposit covered by 400 ft of overburden. Figure A.3 shows that the choice of 30 years does not critically affect the optimal mine width. It also shows that if the evaluation period were 20 years, then the 4000-ft mine width is still favored over a 3000-ft width. The crossover point occurs at 16 years. Even if the evaluation period is as short as 10 years, the choice of a 4000-ft mine width does not give significantly different results from those of a 3000-ft width. Only when the evaluation period is short does the 4000-ft mine width become suspect. For those periods, however, the stripping ratio is unfavorable at any width and surface mining is not likely to occur.

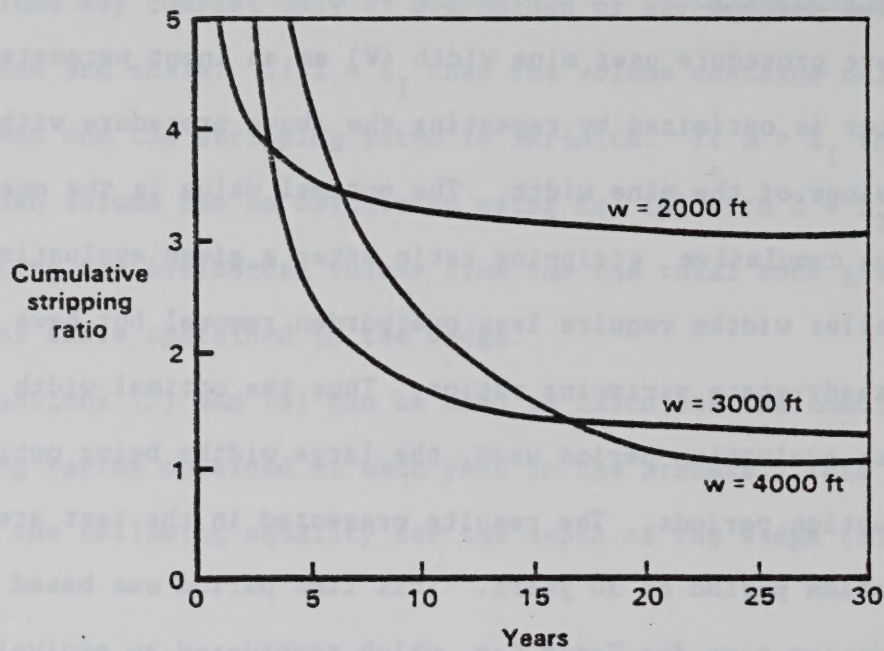


Fig. A.3 -- The effect of mine width

Appendix B

THE LIMITATIONS OF STRIPPING RATIO

Stripping ratio accounts for most costs in a surface mining operation; however, the ultimate profitability of an operation cannot be determined by one simple parameter. Stripping ratio does not include all the factors going into a financial analysis. Notable exceptions are haulage distances and the costs incurred for initial mine development (power, roads, etc.). There has been some concern that these other costs could eliminate the economies of scale discussed in the text. The main argument is the increased haulage distance required for larger mines. Since there are no operational oil shale surface mines, there is of course no definitive evidence. However, we believe that for the production levels contemplated in this report, the available evidence points to the indicated economies of scale.

The referenced study by Suntech is perhaps the most complete engineering and cost analysis of an oil shale surface mine. That study analyzes a mine on the western edge of the basin and considers production rates larger than 250,000 bpd. A 250,000 bpd mine is at the upper end of the production rates contemplated in this Note. The two smallest cases in the Suntech study were 250,000 bpd and 625,000 bpd with mine widths of about 9,000 ft and 15,000 ft, respectively.[1] As shown in Fig. 9 of our Note, we would not expect any significant difference in stripping ratio for these two Suntech mines. This is because stripping ratios for western-edge deposits do not decrease

[1] In our report the 50,000 bpd center basin mine had a width of about 5,000 ft and the 250,000 bpd mine had a width of about 9,000 ft. Thus haulage distances may be less significant for our cases.

significantly for production rates greater than 150,000 bpd. We would therefore not expect any difference in mining costs. The Suntech study confirmed this result by showing that undiscounted mining costs were essentially identical for the 250,000 bpd and 625,000 bpd cases. Thus the costs associated with haulage distances did not dominate the stripping-ratio cost-contribution. One reason is that the somewhat increased haulage costs were balanced by economies of scale in initial mine development. Since increased haulage costs occur late in the mining process, discounting costs strengthens the case for economies of scale. The higher the discount factor, the more tendency toward economies of scale. However, independent of the discount factor, the Suntech study appears to indicate that stripping ratio is a good figure of merit for mine widths of up to 15,000 ft, and depending on the discount factor, perhaps up to 25,000 ft. These widths are well beyond the mine sizes contemplated in our study. Finally, it should be noted that Suntech studied mine widths of more than 100,000 ft. Stripping ratios are still relevant for these widths, but it is clear that haulage distances take on increased importance.

The above arguments point to the need for site-specific cost analysis to determine optimal mine production levels. Haulage profiles must be defined and financial assumptions included. However, stripping ratios do drive costs, and for center basin deposits, stripping ratios are extremely sensitive to production rates up to about 300,000 bpd. Given the above evidence, we therefore expect the need for sizable mining operations to efficiently extract center basin deposits.

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showed that the Colorado Fuel and Iron Company was the largest

producer of coal in the United States in 1917.

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